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ABSTRACT

Photometric Hα and Hβ line indices for 71 B stars in seven galactic clusters are presented. Some stars in three of the clusters were observed at two epochs. Using these data nine Be stars were identified. Three of them were previously detected as emission-line stars, while six do not appear to have been previously recognized as such. Of the 62 stars for which we find no indication of emission, three were previously found to exhibit emission. We find that emission-line objects are absent among the most luminous early B giants.

Subject headings: open clusters and associations: general — stars: emission-line, Be — stars: evolution

1. INTRODUCTION

Balmer line emission in hot stars has been known for more than a century. Nonetheless, Be stars remain an area of active research. Questions such as the evolutionary stage of Be stars, the cause of variability in the emission, the mechanism which produces the circumstellar envelope, the mechanism underlying the continuum light variations and even the basic properties of the stars are still uncertain (see, e.g., Abt 1987; Percy 1987; Slettebak 1987 for reviews of some outstanding issues).

As with other types of stars, when Be stars are members of clusters various of their properties can be deduced. Accordingly, a number of investigators have searched clusters for Be stars (e.g., Schild & Romanishin 1976; Abt 1979; Sanduleak 1979; Lloyd Evans 1980; Mermilloid 1982). Unfortunately, the information in these studies comes from a variety of sources and various methodologies were used. In particular, the sensitivity of various surveys must differ, which affects the statistics of Be star occurrence.

In this paper we describe an attempt to improve this situation through a photometric search for Be stars in seven northern clusters (out of a total of about a dozen in which all the B stars are bright enough for our instrumentation). This study is homogeneous in terms of sensitivity and provides a quantitative measure of the emission or places quantitative limits on undetected emission.

2. OBSERVATIONS

We have used the Behlen Observatory CCD photometer on the 0.76 m telescope to search young clusters for Be stars. The CCD system and the methods of reduction have been described by Schmidt (1988, 1990a, b). For the observations reported here we have used two pairs of interference filters centered on Hα and Hβ. Each pair consisted of the broad-band filter ($\Delta\lambda_{FWHM}$ = 193 Å and 200 Å, respectively) and a narrow-band filter ($\Delta\lambda_{FWHM}$ = 19 Å and 29 Å, respectively). Following the technique devised by Strömgren (1963) and further developed by Crawford (1973), the ratio of flux through the broad filter to that through the narrow filter is used as a measure of line strength. We denote these ratios, expressed in the form of magnitudes, by α and β. As the line absorption increases the indices increase but emission with cause them to decrease. It should be noted that the α and β indices are insensitive to wavelength-dependent effects such as atmospheric extinction and interstellar reddening.

To detect Be stars, we adopt a method previously used by Andrew (1965), Feinstein (1974), and Crawford, Barnes, & Perry (1975). Since the absorption in Hα and Hβ is correlated for B stars, a plot of the two indices for nonemission-line objects will exhibit a well-defined (nearly linear) sequence. However, since Hα emission is much stronger than Hβ emission in Be stars, such objects will fall off the sequence.

A similar technique was recently described by Grebel, Richtler, & DeBoer (1992). However, their method differs in that it employs only a intermediate-bandwidth filter, $\Delta\lambda$ = 48.5 Å, centered on Hα and the Strömgren y and b filters. It takes less integration time than our method because it employs fewer filters which are all broader than our two narrow-band filters. However, it is affected by atmospheric extinction and interstellar reddening.

Table 1 lists the seven clusters we have observed, the Julian dates on which they were observed, and the source of the star identifications and UBV photometry. Note that some clusters were observed on two or three nights to increase the number of stars and to check for variability. Table 2 presents the observational data for the individual stars. Column (1) identifies the stars while column (2) lists the Q values that were calculated with Johnson & Morgan's (1953) equation,

$$Q = (U-B) - 0.72(B-V) .$$

$B-V$ and $U-B$ were taken from the sources listed in Table 1. Q is a reddening-independent temperature indicator which will be used below in analyzing our measurements. Halbedel (1993) has shown that its use is valid for Be stars. When there was no UBV photometry, we have estimated Q from Halbedel's Q-spectral type relation. In these cases, the value is enclosed in parentheses. Stars with Q greater than zero are A stars which will not be considered further in this paper. Column (3) and (4) give the α and β indices. Since many of the observations were made on nonphotometric nights, we have adjusted to zero points to match the bulk of the stars in each cluster to the

[1] The views expressed in this paper are those of the authors and do not reflect the views of the National Science Foundation.

TABLE 1

CLUSTERS OBSERVED

Cluster (1)	HJD (−2,440,000) (2)	Source (3)
NGC 869	7819, 7917	1
NGC 884	7918, 8194	1
NGC 957	7917, 7918, 7819	2
NGC 1912[a]	7834	2
NGC 6910	8113	2
NGC 7510	8146	2
IC 4996	8113	2

[a] NGC 1912 = M38.

SOURCES.—(1) Identifications from Oosterhoff 1937 and *UBV* photometry from Mermilloid 1976. (2) Identifications and *UBV* photometry from Hoag et al. 1961. Numbers less than 100 refer to the list of photometric magnitudes and colors printed with the cluster chart by Hoag et al., while numbers greater than 100 refer to the tables of photographic photometry in the appendix of the paper. The latter are assigned numbers in order of their appearance in the table beginning with 101. We give both numbers for stars included in both lists.

sequence for nonemission-lines stars of NGC 1912 in the α versus Q and the β versus Q diagrams. This assumes that most of the stars are nonemission-line objects and places all the data on a consistent instrumental system for convenience. It does not affect the conclusions drawn below regarding emission.

Crawford, Glaspey, & Perry (1970) measured β indices in NGC 869 (h Per) and NGC 884 (χ Per) while Crawford, Barnes, & Hill presented such information for NGC 6910. There are 20 stars in common between our sample and these papers (of which nine appear twice in Table 2). Unfortunately, the range of β indices is too small to determine a meaningful slope for the relationship between the two sets of measurements. Accordingly, we have used the widths of our filters to infer the slope from the calculations of Schmidt & Taylor (1979) and have then calculated a zero point from the stars in common. The resulting transformation is

$$\beta_c = 0.912\beta_G + 0.641 ,$$

where β_c represents values of the index on the standard system and β_G represents our indices. The rms scatter of the individual points about this transformation is ± 0.036 mag in agreement with the estimate of our accuracy given below.

In Figures 1 and 2 we plot the α and β indices against Q. While Q is temperature-dependent, the line indices are also dependent on luminosity. Nonetheless, the temperature dependence in the hydrogen lines dominates and we expect a well-defined relationship for nonemission-line B stars. In Figure 2 one point, that corresponding to star 1132 in NGC 869 on JD 7917, falls below the relation defined by the other points. A comparison with the measurements of the star on JD 7819 shows that both α and β differ significantly between the two nights. Since a careful examination of the original data gives no indication of any difficulty with the measurements, we have no explanation for this behavior. Clearly the extreme values of the indices for star 1132 on JD 7917 suggest that they be treated with caution.

In each plot the solid line was fitted by eye through the majority of the stars which are assumed to be nonemission-line stars. Points which fall below the line are indicative of Be stars. The rms scatter about these lines (ignoring the presumed Be stars) is 0.035 mag in both α and β. Although some of this scatter may be due to luminosity effects and to our normal-

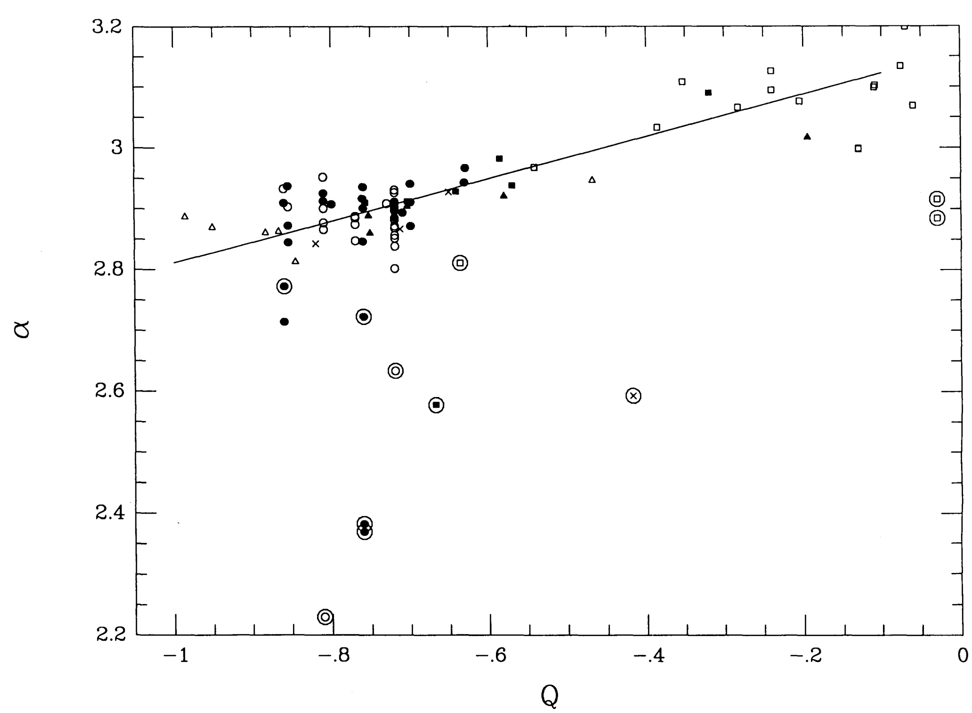

FIG. 1.—Plot of the α index vs. Q. Solid line is an eye fit to the nonemission-line sequence. Symbols denote the various clusters as follows: *solid circles*, NGC 869; *open circles*, NGC 884; *solid squares*, NGC 957; *open squares*, NGC 1912; *solid triangles*, NGC 6910; *open triangles*, NGC 7510; *X*s, IC 4996. Points corresponding to stars we have designated as emission-line stars (col. [6] of Table 2) are circled.

TABLE 2

PHOTOMETRIC DATA FOR CLUSTER STARS

STAR (1)	Q (2)	α (3)	β (4)	Δα (5)	Be Present (6)	STAR? Previous (7)
NGC 869 (JD 7819)						
843	−0.76	2.847	2.168	0.051		
911	−0.72	2.912	2.236	0.053		
922	−0.86	2.846	2.114	−0.001		
926	−0.63	2.943	2.274	0.059		
936	−0.72	2.897	2.173	0.005		
963	−0.76	2.723	2.156	0.162	Yes	
1004	−0.72	2.906	2.266	0.089		
1078	−0.81	2.913	2.176	−0.008		
1085	−0.76	2.917	2.188	0.001		
1116	−0.86	2.938	2.108	−0.099		
1132	−0.86	2.873	2.156	0.013		
1161	−0.76	2.370	2.114	0.475	Yes	Yes
NGC 869 (JD 7917)						
922	−0.86	2.773	2.150	0.106	Yes	
926	−0.63	2.967	2.244	0.005		
929	(−0.70)	2.872	2.196	0.052		
936	−0.72	2.886	2.181	0.023		
963	−0.76	2.936	2.258	0.049		
978	−0.71	2.894	2.165	0.000		
980	(−0.72)	2.902	2.202	0.028		
991	(−0.70)	2.941	2.194	−0.019		
1004	−0.72	2.899	2.198	0.027		
1078	−0.81	2.926	2.149	−0.048		
1080	(−0.70)	2.911	2.202	0.019		
1085	−0.76	2.901	2.170	−0.002		
1116	−0.86	2.910	2.140	−0.041		
1132	−0.86	2.715	1.885	−0.097		
1133	(−0.80)	2.908	2.095	−0.083		
1161	−0.76	2.383	2.089	0.436	Yes	Yes
NGC 884 (JD 7918)						
2088	−0.77	2.848	2.141	0.022		Yes
2114	−0.72	2.857	2.222	0.094		
2139	−0.72	2.872	2.229	0.086		
2185	−0.72	2.634	2.190	0.284	Yes	
2196	−0.77	2.885	2.228	0.072		
2227	−0.72	2.802	2.134	0.061		
2232	−0.72	2.902	2.132	−0.039		
2235	−0.81	2.867	2.100	−0.036		
2242	−0.81	2.229	2.124	0.625	Yes	Yes
2246	−0.77	2.875	2.119	−0.026		
2251	−0.73	2.909	2.201	0.021		
2296	−0.81	2.952	2.164	−0.058		
2299	−0.86	2.904	2.127	−0.046		
2311	−0.72	2.882	2.208	0.055		
2371	−0.72	2.911	2.158	−0.023		Yes
NGC 884 (JD 8194)						
2139	−0.72	2.869	2.211	0.070		
2227	−0.72	2.852	2.118	−0.005		
2232	−0.72	2.931	2.181	−0.022		
2235	−0.81	2.878	2.143	−0.006		
2246	−0.77	2.888	2.161	0.002		
2296	−0.81	2.901	2.123	−0.049		
2299	−0.86	2.933	2.140	−0.064		
2311	−0.72	2.927	2.156	−0.042		
2371	−0.72	2.839	2.122	0.012		

STAR (1)	Q (2)	α (3)	β (4)	Δα (5)	Be Present (6)	STAR? Previous (7)
NGC 957						
1/101	−0.70	2.912	2.157	−0.025		
4/101	−0.76	2.910	2.179	−0.002		Yes
110	−0.59	2.982	2.229	−0.024		
9/112	−0.64	2.928	2.265	0.065		
11/114	−0.67	2.578	2.187	0.338	Yes	Yes
13/119	−0.57	2.938	2.239	0.030		
132	−0.32	3.090	2.334	−0.028		
NGC 1912 (JD 7834)						
106	−0.64	2.811	2.212	0.130	Yes	
111	−0.20	3.076	2.311	−0.037		
114	−0.28	3.066	2.339	0.000		
137	−0.35	3.108	2.471	0.088		
16/138	−0.11	3.102	2.409	0.033		
144	−0.08	3.134	2.430	0.022		
18/148	−0.54	2.968	2.249	0.010		
152	−0.39	3.033	2.301	−0.004		
NGC 1912 (JD 7917)						
113	−0.13	2.999	2.244	−0.027		
120	−0.24	3.094	2.372	0.004		
121	−0.03	2.916	2.332	0.142	Yes	
129	−0.11	3.099	2.369	−0.004		
134	−0.07	3.199	2.415	−0.059		
13/135	−0.06	3.069	2.402	0.058		
NGC 1912 (JD 7918)						
104	−0.05	2.927	2.138	−0.060		
113	−0.13	2.998	2.236	−0.034		
120	−0.24	3.126	2.385	−0.015		
121	−0.03	2.885	2.327	0.168	Yes	
NGC 6910						
4/105	−0.19	3.017	2.324	0.034		
7/107	−0.75	2.889	2.191	0.031		
108	−0.58	2.921	2.167	−0.024		
10/111	−0.75	2.860	2.151	0.020		
11/114	0.47	2.823	2.148	0.055		
126	−0.70	2.904	2.174	−0.001		
NGC 7510						
3/103	−0.95	2.870	2.132	−0.007		
4/104	−0.47	2.947	2.222	0.004		
105	−0.87	2.864	2.134	0.000		
5/106	−0.88	2.862	2.136	0.005		
107	−0.99	2.887	2.154	−0.003		
108	−0.85	2.814	2.124	0.041		
IC 4996						
102	−0.82	2.844	2.178	0.064		
109	−0.65	2.928	2.208	0.009		
9/117	0.00	2.911	2.142	−0.039		
11/118	0.07	2.895	2.189	0.024		
125	−0.71	2.867	2.172	0.035		
14/139	−0.42	2.593	2.215	0.351	Yes	

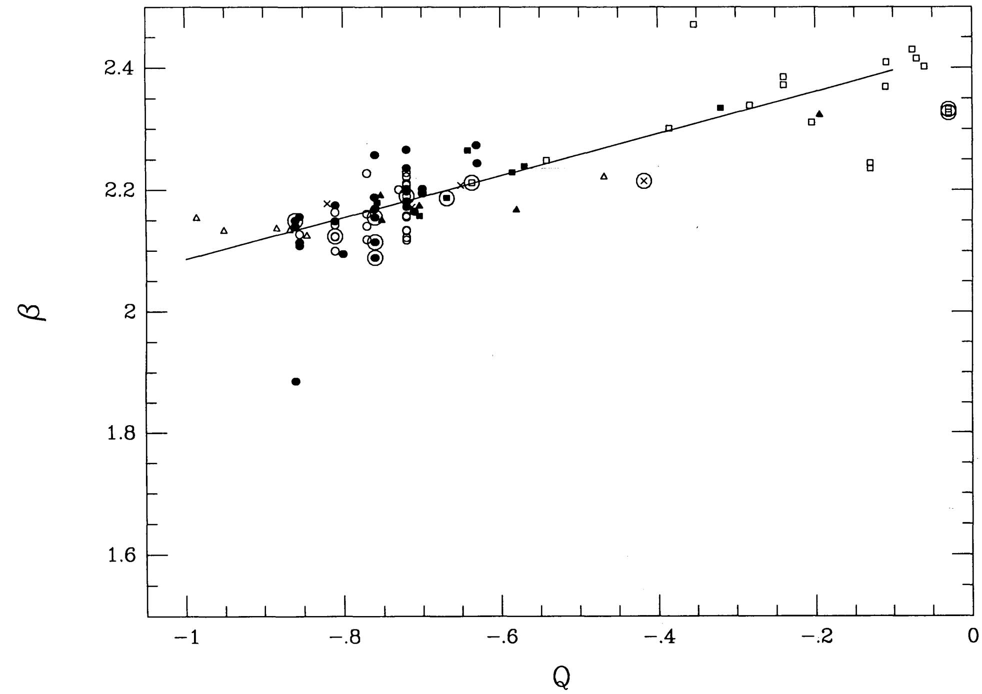

FIG. 2.—Plot of the β index vs. Q. Solid line is an eye fit to the nonemission-line sequence. Symbols have the same meaning as in Fig. 1.

ization of the indices of the various clusters, we will use it as an estimate of the uncertainties.

The way in which the error in the line index propagates into the emission-line strength or equivalent width depends on the flux of the emisson compared to the photospheric residual intensity within the narrow-band filter. At one extreme where a strong emission feature dominates the flux in the narrow-band filter, the 3.5% error in the α or β index translates into a 3.5% error in the equivalent width of the emission. At the other extreme, where the emission is weak compared with the total flux in the narrow band, the 3.5% error translates into an error of about 0.7 Å in equivalent width (for a 19 Å passband). Thus we are able to detect emission with high certainty at equivalent width of about 2 Å. In the cluster studies cited above there are very few Be stars listed with emission this weak.

3. DISCUSSION

In comparing Figure 1 with Figure 2, it is obvious that the α index shows considerable scatter below the line while the β index does not. As mentioned above, this is due to the fact that the emission in Hα is much stronger than that in Hβ. Plotting the deviations of β from the line in Figure 2 against those of α from the line in Figure 1 gives a slope of about 0.1. Thus, in what follows we can neglect the effects of emission on β.

Figure 3 shows the plot of α versus β. A line has been fitted through the majority of stars which are taken to be nonemission-line objects. Following Crawford et al. (1975) we have defined $\Delta\alpha$ as the horizontal displacement of a point from the nonemission sequence. It is positive for emission-line stars. Column (5) in Table 2 lists $\Delta\alpha$ for all the stars. Errors in α dominate the uncertainty so $\Delta\alpha > 0.10$ will be adopted as a detection of a Be star at the 3 σ level. Using this criterion, 11 detections of emission in nine different stars are indicated in column (6) of Table 2. There are an additional half-dozen stars which have slightly smaller values of $\Delta\alpha$ and are probably weak emission-line stars. We indicate in column (7) those stars which are listed as Be stars in the catalog of Mermilliod (1982).

We find three previously known Be stars which are still active. Three other stars previously observed to be Be stars no longer show emission. Six stars were found to be Be stars in our survey but are not listed as such in the catalog. Two stars in NGC 869 varied sufficiently in the 100 days between our observations to be detected as emission stars in one instance but not the other.

The differences as to which stars we detect as emission-line objects compared with Mermilliod's catalog can be attributed to several factors. These include the sensitivity to emission of the photometric method, previous incompleteness in some clusters (and the fact that some investigators do not identify which B stars in clusters were observed and found to lack emission), and secular variations in the emission. Given these factors and the small number of stars with detected emission, it is not possible to draw conclusions regarding either the incidence of Be stars of the timescale and duty cycle of the Be phenomenon. However, the information in Table 2 does provide the basis for obtaining such information from future observations.

In Figure 4 we have plotted the H-R diagram for all the B stars in Table 2. We have used Q for the color coordinate as it is a sensitive temperature indicator for early-type stars. The absolute magnitudes were calculated using the color excesses and distance moduli from Hagen (1970). It can be seen that the majority of the stars occupy a band between $Q = -0.6$ and $Q = -0.9$ which extends from the zero-age main sequence (ZAMS) to about 4 mag above it. These stars belong to the group that Mermilliod (1982) referred to as "early (B0.5–B3)e stars." The following discussion will be concerned with this group of stars.

The early group includes seven of the nine Be stars from Table 2. It can be seen that the Be stars are scattered from the

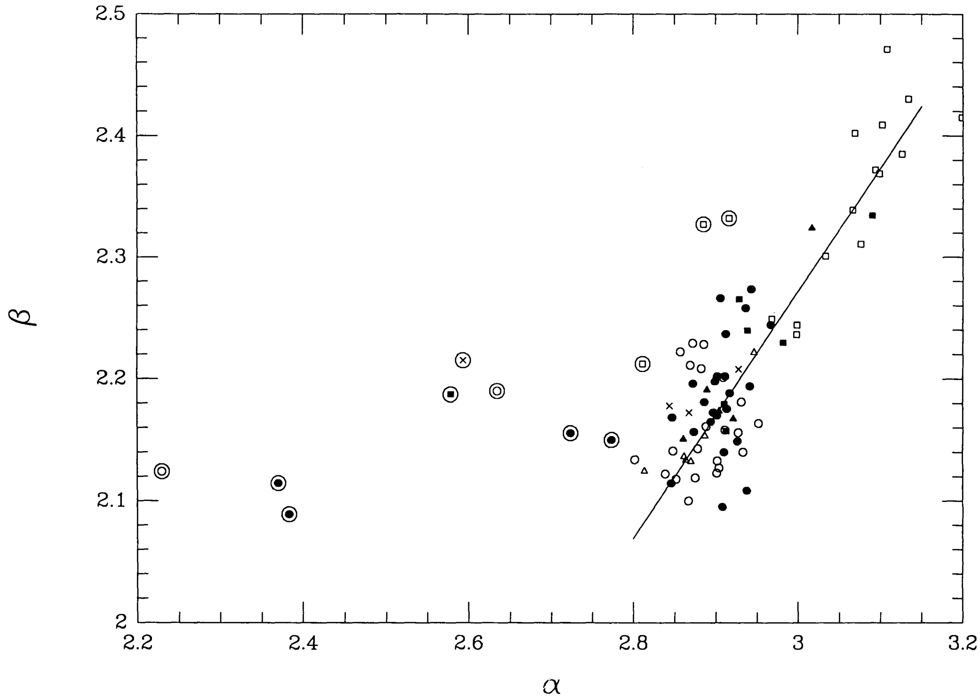

FIG. 3.—Plot of β vs. α. The line indicates the sequence of nonemission B stars. Emission line stars will be displaced toward the left from the line. Symbols have the same meaning as in Fig. 1.

ZAMS to an absolute magnitude of $M_V = -4.0$. They constitute 22% of the stars in that range. On the other hand, no Be star is found among the 22 stars brighter than this limit. If a similar proportion of the bright stars exhibit emission as the fainter stars, the probability of finding none due to random sampling is less than 1%. Applying a t-test to the magnitude difference between the nonemission-line B stars and the Be stars shows that the mean absolute magnitudes of the two groups differ at a confidence level greater than 95%. Thus statistical tests support the conclusion that Be stars are found among the brightest B stars.

The conclusion of the previous paragraph is largely dependent on the clusters NGC 869 and NGC 884 (h and χ Per). If we consider only these two clusters, the smaller number of stars reduces the statistical significance of our conclusion. Nonetheless, the probability of finding no stars with emission above

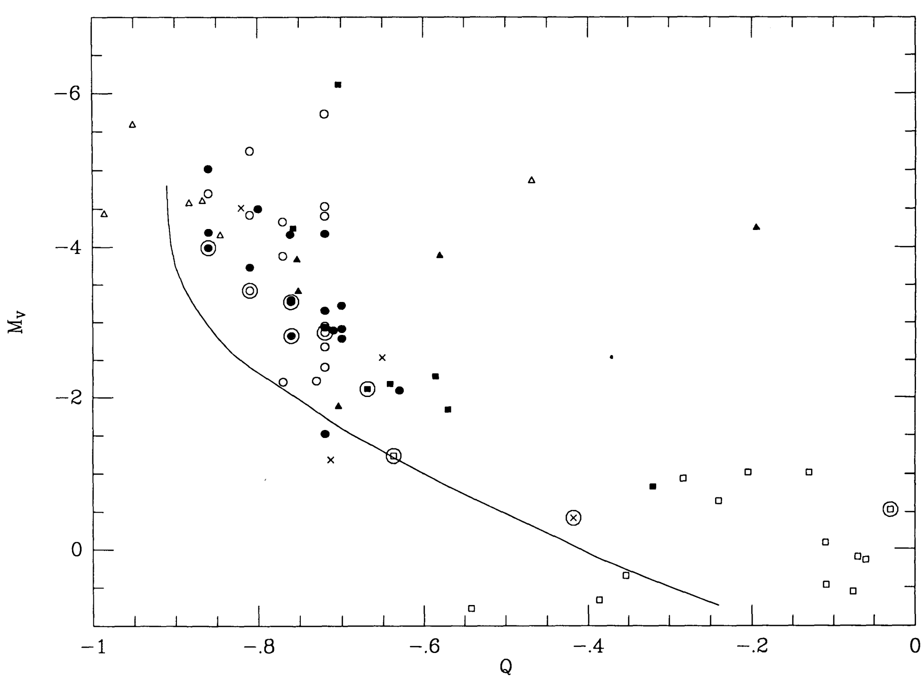

FIG. 4.—The H-R diagram for all the B stars in Table 2. Symbols have the same meaning as in Fig. 1. The continuous curve is the zero-age main sequence.

$M_V = -4.0$ by chance is only 1.5%. The removal of the faintest two emission-line stars has reduced the difference between the mean absolute magnitudes of the two groups below statistical significance. However, an F-test (which tests whether the variance of two samples are the same) shows that the distribution of Be stars differs from that of the nonemission-line stars with greater than 92% confidence. Our conclusion that the Be stars are not uniformly distributed with regard to absolute magnitude stands. However, with only these two clusters we would have to conclude that the Be occupy a band which reaches neither the most luminous B stars nor the ZAMS.

Our statement that Be stars are absent among the brightest ($M_V < -4.0$) B stars is somewhat more restrictive than Mermilliod's (1982, p. 48) conclusion that "Be stars occupy the whole main-sequence band (from the ZAMS to the TAMS)" or Slettebak's (1985, p. 781) statement that "the Be stars in the 12 clusters studied here may be found anywhere between the ZAMS and the outer fringes of the main sequence." The points in Figure 4 which are above our cutoff for emission are clearly part of the sequence of stars evolving up from the ZAMS. Only stars at least a magnitude above the cutoff have reached the phase of rapid evolution into red giants.

In a later discussion, Slettebak (1988, p. 782) characterized the location of the Be stars in the H-R diagram by saying "Be stars may be found anywhere between the zero-age main sequence and the giant region." Schild (1965) has assigned most of the NGC 864 and NGC 889 stars plotted in Figure 4 to luminosity class V (27 stars) or IV (two stars) with only three giants (class III) and one class II star. Again, our magnitude cutoff for the Be phenomenon is more restrictive than Slettebak's statement.

As previous investigators have pointed out (see Slettebak 1988 for a discussion and references), intrinsic reddening and rotation may affect the colors and magnitudes of Be stars. Hence, their location in the H-R diagram cannot necessarily be attributed solely to their evolutionary state.

By using Q in Figure 4, we have removed the effect of intrinsic reddening from the abscissa at least to the degree that circumstellar reddening resembles interstellar reddening. On the other hand, the absolute magnitudes will still be affected. From Slettebak's (1985) discussion, it is apparent that intrinsic reddening for most Be stars is less than 0.1 mag in $B-V$ which will produce too small a change in the plotted absolute magnitudes to account for the lack of bright Be stars in Figure 4. As a further test of this, we have plotted the $B-V$ colors of the stars from NGC 869 and NGC 884 against Schild's (1965) spectral types. While there is considerable scatter in color at any particular spectral type, only one of the Be stars, number 2242, falls outside the main group of stars; it is about 0.15 mag too red for its spectral type. In Figure 4, it is located at $Q = -0.81$, $M_V = -3.42$. If we were to increase its luminosity by 0.45 to take into account the presumed intrinsic reddening, it would still not fall above our upper limit for Be stars. From these considerations, it appears unlikely that the distribution of Be stars in Figure 4 can be explained by intrinsic reddening.

Collins & Sonneborn (1977) calculated the effects of rotation on both the colors and absolute magnitudes of main-sequence stars. Slettebak, Kuzma, & Collins (1980) conducted further calculations to explore the effects of rotation on spectral classification. The absolute magnitudes of B stars are affected too little and generally in the wrong sense to account for our upper limit for Be star luminosities. The spectral types or colors of a rapidly rotating star are later or redder than an equivalent slow rotator by as much as 1.5 spectral subclasses. However, while this could move ZAMS stars into the region of the evolved Be stars (as suggested by Collins & Sonneborn), it too fails to account for the lack of Be stars among the brighter cluster B stars. In addition, if we postulate that the Be stars in NGC 869 and NGC 884 are actually ZAMS stars, they would all be blue stragglers, which seems improbable.

We conclude that the lack of Be stars among the brightest members of the early group is unlikely to be accounted for by intrinsic reddening or rapid rotation; the Be phenomenon appears to be absent among the most evolved B stars. Whether this conclusion applies just to NGC 869 and NGC 884 cannot be determined from the present data. Additional observations of other clusters are needed to address this point. Further observations of the stars in these two clusters to extend the sample to more objects and to determine the rule of secular variation would be also useful.

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